Chapter 13 "... but What is it Good for?"

As in other scientific fields, nuclear scientists generally work with a great interest and excitement for the science. Understanding the building blocks of nature and the physical laws that govern them is the ultimate goal. On the other hand, members of the public are the taxpayers who finance most research in basic science and, understandably, often want to see something more concrete emerge from their investments, some further benefit to society. In the century since Rutherford discovered the nucleus, numerous applications take advantage of one or more of the following: 1) the properties of nuclei, 2) measurement techniques developed in nuclear physics, 3) particle accelerators, and 4) other tools of nuclear science such as detectors.

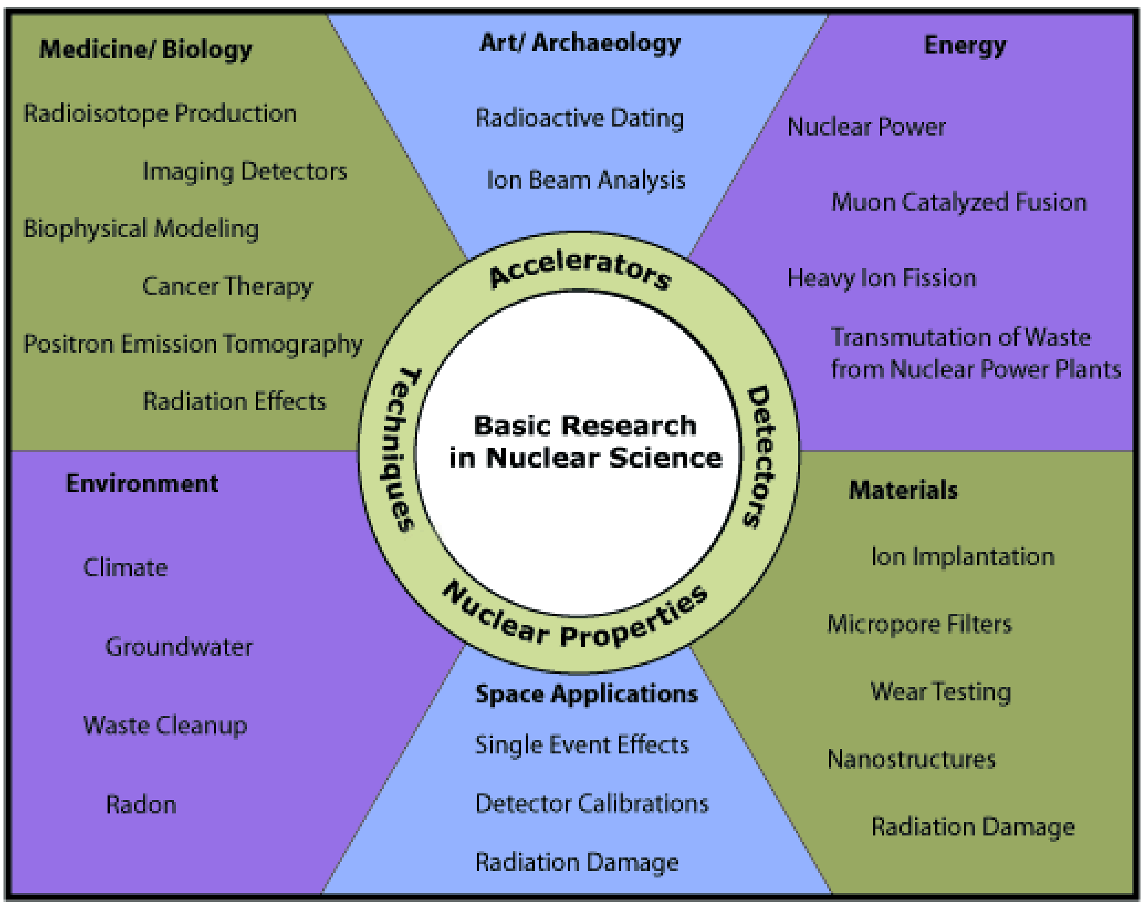

Fig. 13-1. Applications of nuclear science.

These applications benefit disciplines as diverse as medicine, biology, art, archaeology, energy, materials science, space exploration, and the environment. Many of these applications are detailed in Fig. 13-1. Only, a sample of them will be described in this chapter. The energy applications of nuclear science are described separately in Chapter 14.

The following examples are illustrative of the wide variety of applications of nuclear science. While some of these applications are very specific and have little effect on our daily lives, many of these applications are all pervasive. We probably use some electricity generated by nuclear reactors, protect our homes with smoke alarms, and have all been affected by the geopolitics of nuclear weapons.

Smoke Detectors

Most common smoke detectors (Fig. 13-2) contain a small amount of ^{241}Am, a radioactive isotope. ^{241}Am is produced and recovered from nuclear reactors. Alpha particles emitted by the decays of ^{241}Am ionize the air (split the air molecules into electrons and positive ions) and generate a small current of electricity that is measured by a current-sensitive circuit. When smoke enters the detector, ions become attached to the smoke particles, which causes a decrease in the detector current. When this happens, an alarm sounds. These detectors provide warning for people to leave burning homes safely. Many lives have been saved by the their use.

Fig. 13-2. A common smoke detector.

Because the distance alpha particles travel in air is so short, there is no risk of being exposed to radiation by having a smoke detector in the house. Since ionization-type smoke detectors contain radioactive materials, they should be recycled or disposed of as radioactive waste. It is important to follow the instructions that come with the smoke alarm when they need to be discarded.

Nuclear Medicine

Radioisotopes for diagnosis and treatment

One major use of radioisotopes is in nuclear medicine. Of the 30 million people who are hospitalized each year in the United States, 1/3 are treated with nuclear medicine. More than 10 million nuclear-medicine procedures are performed on patients and more than 100 million nuclear-medicine tests are performed each year in the United States alone. A comparable number of such procedures are performed in the rest of the world.

There are nearly one hundred radioisotopes whose beta and/or gamma radiation is used in diagnosis, therapy, or investigations in nuclear medicine. The most used radioisotopes were discovered before World War II using the early cyclotrons of Ernest Lawrence, with the initial applications to medicine being developed by his brother John Lawrence. Some of the most well known radioisotopes, discovered by Glenn Seaborg and his coworkers, are ^{131}I (discovered in 1938), ^{60}Co (1937), ^{99m}Tc (1938), and ^{137}Cs (1941). By 1970, 90 percent of the 8 million administrations per year of radioisotopes in the United States utilized either ^{131}I, ^{60}Co, or ^{99m}Tc. Today, ^{99m}Tc, with a half-life of 6 hours, is the workhorse of nuclear medicine. It accounts for more than 10 million diagnostic procedures a year in the United States. It is used for brain, bone, liver, spleen, kidney, lung and thyroid imaging as well as for blood-flow studies.

^{131}I, with a half-life of 8 days, is used to diagnose and treat thyroid disorders. Seaborg’s mother was one of the first to benefit from the use of this radioisotope that her son had discovered. Fatally ill from hyperthyroidism, (a related condition from which her sister died), diagnosis and treatment with ^{131}I led to her complete recovery and a long life. Former President George Bush and First Lady Barbara Bush are some notable people who were successfully treated for Graves' disease, a thyroid disease, with ^{131}I. Radioactive iodine treatment is so successful that it has virtually replaced thyroid surgery.

a) b)

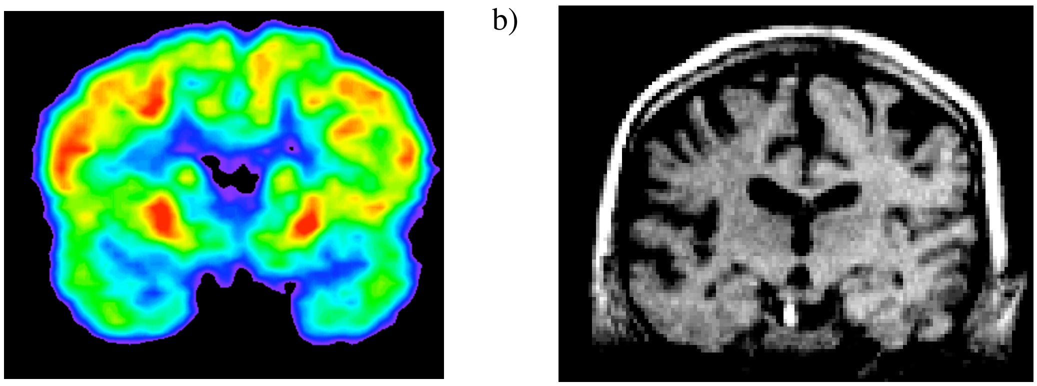

Fig. 13-3. a) PET image of the human brain. b) MRI image of the human brain.

A very effective role for radioisotopes in nuclear medicine is the use of short-lived positron emitters such as ^{11}C, ^{13}N, ^{15}O, or ^{18}F in a process known as Positron Emission Tomography (PET). Incorporated in chemical compounds that selectively migrate to specific organs in the body, diagnosis is effected by detecting annihilation gamma rays—two gamma rays of identical energy emitted when a positron and an electron annihilate each other. These gamma rays have the very useful property that they are emitted in exactly opposite directions. When both are detected, a computer system may be used to reconstruct where the annihilation occurred. By attaching a positron emitter to a protein or a glucose molecule, and allowing the body to metabolize it, we can study the functional aspect of an organ such as the human brain. The PET image shows where the glucose has been absorbed (Fig. 13-3a).

PET imaging becomes even more valuable when we can observe the functional image compared to the anatomical image. Magnetic Resonance Imaging (MRI)—originally known as Nuclear Magnetic Resonance Imaging—can provide very detailed images of the anatomy as shown in the second image shown in Fig. 13-3b. These techniques provide researchers a better understanding of what is healthy tissue versus what is diseased.

Cancer therapy

The radioisotope ^{60}Co emits gamma rays that are used to destroy cancer cells. Hundreds of thousands of Americans who suffer from cancer have been treated in this way. Every year millions of cubic meters of medical products and equipment are sterilized by irradiation worldwide. The isotope ^{137}Cs has found substantial applications as a gamma-ray source in medical therapy, similar in its use to that of ^{60}Co.

Cancer treatment with beams of massive ions directly from an accelerator has gained increasing utilization in the last decade. Unlike gamma rays, which distribute their energy equally in healthy as well as cancerous cells, massive particles such as protons or alpha particles will deposit the bulk of their energy just before they stop. If the energy is well chosen, most of the energy will be dumped into the tumor and not into the surrounding healthy tissue. Using three dimensional water degrader columns, the shape of the tumor can be mapped out and selectively irradiated. Dedicated accelerators are now being built to continue this work at medical centers. In the United States, the Loma Linda Medical Center in California is now operating a proton synchrotron for therapy, and a second facility is being built at Massachusetts General in Boston.

Boron Neutron Capture Therapy (BNCT) is under development for the treatment of glioblastoma multiforma, a brain cancer which afflicts some 12,500 people a year in the US alone and is almost impossible to treat by currently available means. In BNCT, boron is synthesized into compounds that are selectively taken up by cancerous cells in the brain and not by healthy ones. In subsequent irradiation by low-energy neutrons (from a reactor or accelerator), the following neutron-capture reaction occurs:

$$^{10}B + n \rightarrow {}^{11}B \rightarrow {}^{7}Li + {}^{4}He.$$

The recoiling lithium and helium nuclei have short ranges and large energy losses. These particles destroy the cancerous cells and spare the surrounding healthy tissue.

Radioactive Dating

The technique of comparing the abundance ratio of a radioactive isotope to a reference isotope to determine the age of a material is called radioactive dating. Many isotopes have been studied, probing a wide range of time scales.

The isotope ^{14}C, a radioactive form of carbon, is produced in the upper atmosphere by neutrons striking ^{14}N nuclei. The neutron is captured by the ^{14}N nucleus and knocks out a proton. Thus, we have a different element, ^{14}C. The isotope, ^{14}C, is transported as $^{14}CO_2$, absorbed by plants, and eaten by animals. If we were to measure the ratio of ^{14}C to ^{12}C today, we would find a value of about one ^{14}C atom for each one trillion ^{12}C atoms. This ratio is the same for all living things—the same for humans as for trees or algae.

Once living things die, they no longer can exchange carbon with the environment. The isotope ^{14}C is radioactive, and beta-decays with a half-life of 5,730 years. This means that in 5,730 years, only half of the ^{14}C will remain, and after 11,460 years, only one quarter of the ^{14}C remains. Thus, the ratio of ^{14}C to ^{12}C will change from one in one trillion at the time of death to one in two trillion 5,730 years later and one in four trillion 11,460 years later. Very accurate measurements of the amount of ^{14}C remaining, either by observing the beta decay of ^{14}C or by accelerator mass spectroscopy (using a particle accelerator to separate ^{12}C from ^{14}C and counting the amount of each) allows one to date the death of the once-living things.

Perhaps you have heard of Iceman, a man living in the Alps who died and was entombed in glacial ice until recently when the ice moved and melted. The man's body was recovered and pieces of tissue were studied for their ^{14}C content by accelerator mass spectroscopy. The best estimate from this dating technique says the man lived between 3350 and 3300 BC.

The boat of a pharaoh was discovered in a sealed crypt and reassembled in a museum near the pyramids (see Fig. 13-4). Its wood was dated using ^{14}C to be about 4,500 years old.

Fig. 13-4. The pharaoh's funerary boat. © National Geographic Society

Other methods of dating are used for non-living things. ^{40}K decays with a half-life of 1.3×10^9 years to ^{40}Ar, which can be trapped in rocks. A potassium-argon method of dating, developed in 1966, measures the amount of ^{40}Ar arising from the ^{40}K decay and is compared to the amount of ^{40}K remaining in the rock. From the ratio, the time since the formation of the rock can be calculated.

The age of our galaxy and earth also can be estimated using radioactive dating. Using the decays of uranium and thorium, our galaxy has been found to be between 10 and 20 billion years old and the earth has been found to be 4.6 billion years old. The Universe must be older than our galaxy. Within experimental error, this estimate agrees with the 15 billion-year estimate of the age of the Universe.

Neutron Activation Analysis

There are at least 50 elements occurring in nature that have radioactive isotopes with one neutron more than their stable isotopes. This means that the radioactive species can be made by neutron bombardment. This procedure is typically done in a nuclear reactor, although other neutron sources can sometimes be used. The stable nucleus absorbs one neutron and becomes a radioactive nucleus. By detecting the decay of these nuclei, which can be done with great sensitivity, one can measure the concentration of the stable element of interest in the sample.

A simple example of neutron activation analysis involves the measurement of iridium in soils. This is the measurement that led to the theory that the extinction of the dinosaurs, 65 million years ago, was caused by the impact of an asteroid or comet somewhere on Earth. An impact would produce so much debris in the air that earth would receive a large reduction in sunlight and thus fewer plants would grow. With less food available, there would be a devastating reduction in number of animals. This reduction was so severe that most species, including the dinosaurs, became extinct.

In 1979, a group of scientists reported that neutron activation analysis had shown unusual amounts of the element iridium in Italian Cretaceous-Tertiary boundary sediments. Since iridium is a metal, which has very low abundance on earth, they attributed the excess iridium to an impact of a 10-kilometer diameter asteroid. This work, which melded the disciplines of physics (Nobel Laureate Luis Alvarez), geology (his son, Walter Alvarez) and nuclear chemistry (Isadore Perlman, Frank Asaro and Helen Michel), galvanized the scientific world because the concepts presented could be tested by many diverse techniques.

Since the initial report, anomalous amounts of iridium have been found at the Cretaceous-Tertiary boundary in over 100 sites worldwide. Many experiments have confirmed its impact origin.

Industrial Applications

The applications of radioisotopes in industry are numerous. Many types of thickness gauges exploit the fact that gamma rays are attenuated when they pass through material. By measuring the number of gamma rays, the thickness can be determined. This process is used in common industrial applications such as:

1. the automobile industry—to test steel quality in the manufacture of cars and to obtain the proper thickness of tin and aluminum
2. the aircraft industry—to check for flaws in jet engines
3. construction—to gauge the density of road surfaces and subsurfaces
4. pipeline companies—to test the strength of welds
5. oil, gas, and mining companies—to map the contours of test wells and mine bores, and
6. cable manufacturers—to check ski lift cables for cracks.

The isotope ^{241}Am is used in many smoke detectors for homes and businesses (as mentioned previously), in thickness gauges designed to measure and control metal foil thickness during manufacturing processes, to measure levels of toxic lead in dried paint samples, and to help determine where oil wells should be drilled.

The isotope ^{252}Cf (a neutron emitter) is used for neutron activation analysis, to inspect airline luggage for hidden explosives, to gauge the moisture content of soil and other materials, in bore hole logging in geology, and in human cervix-cancer therapy.

In addition, there are manifold uses in agriculture. In plant research, radiation is used to develop new plant types to speed up the process of developing superior agricultural products. Insect control is another important application; pest populations are drastically reduced and, in some cases, eliminated by exposing male insects to sterilizing doses of radiation. Fertilizer consumption has been reduced through research with radioactive tracers. Radiation pellets are used in grain elevators to kill insects and rodents. Irradiation prolongs the shelf life of foods by destroying bacteria, viruses, and molds.

The useful application of radioisotopes extends to the arts and humanities. Neutron activation analysis is extremely useful in identifying the chemical elements present in coins, pottery, and other artifacts from the past. A tiny unnoticeable fleck of paint from an art treasure or a microscopic grain of pottery suffices to reveal its chemical makeup. Thus the works of famous painters can be "fingerprinted" so as to detect the work of forgers.

Neutron scattering has proved to be a valuable tool for studying the molecular structure and motion of molecules of interest to manufacturing and life processes. Accelerators and reactors produce low-speed neutrons with wavelength appropriate to "see" structures of the size of magnetic microstructures and DNA molecules. Neutrons can penetrate deeply into bulk materials and use their magnetic moment or strong interaction forces to preferentially scatter from magnetic domains or hydrogen atoms in long chain nucleosomes. Neutrons are also used in materials surface and interface studies taking advantage of their reflectivity properties. Intense sources of neutrons include: the IPNS at Argonne National Laboratory in Illinois and LANSCE at Los Alamos National Laboratory in New Mexico.

Removal of Land Mines

Wars have been fought around the globe, and land mines were used extensively by the battling parties. There may be up to 100 million abandoned mines just waiting to maim and kill unsuspecting civilians. Techniques similar to airport weapons detectors have been considered for finding and neutralizing these mines without loss of life.

A promising technology involves nuclear quadrupole resonance. Nitrogen, a common component in explosives, has a nucleus with an ellipsoidal shape. Depending on what kind of crystalline structure the nitrogen nuclei find themselves in, their non-sphericity produces a unique set of very narrowly spaced energy levels that is characteristic of the crystalline solid itself. An explosive compound can therefore be identified by the subtle effect of its constituent nitrogen atoms. This technique could also differentiate explosives from scrap metals in the ground. More details may be found in the reference at the end of this chapter.

Radioisotope Power Generation

Long-lived power sources are needed for equipment that is too remote or inaccessible for replacement. By choosing a radioactive element with a long half-life, we can create a long-lived power source. The appropriate element should:

1. produce weakly penetrating radiation that can be easily shielded,
2. a specific power of at least 0.2 kW/kg,
3. have good corrosion resistance,

4. be insoluble in water, and
5. be made of reasonably available material.

Among the transuranium elements, oxides of the alpha-emitting nuclides ^{238}Pu ($t_{1/2}$ = 87.7 years) and ^{244}Cm ($t_{1/2}$ = 18.1 years) are useful fuels. A few grams to kilograms of such nuclides, in appropriately shielded containers, provide intense sources of heat with power levels up to hundreds of watts, since the alpha particles are stopped very easily and their decay energy converted into thermal energy. Using thermoelectric devices without moving parts, it is possible to convert the resultant heat flow into usable electricity.

Such power sources are small, lightweight, and rugged. One of their uses is in the SNAP (Space Nuclear Auxiliary Power) units used to power satellites, or more importantly, to power remote sensing instrument packages. A satellite that used a SNAP source is shown in Fig. 13-5. SNAP sources (fueled by ^{238}Pu) served as the power sources for instrument packages on the five Apollo missions, the Viking unmanned Mars lander, and the Pioneer, Voyager and Cassini probes to Jupiter, Saturn, Uranus, Neptune, Pluto, and beyond.

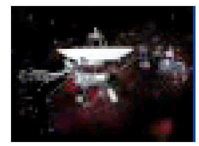

Fig. 13-5. A picture of a satellite that was powered by nuclear energy.

In addition to space applications, radionuclide power sources have been used as terrestrial sources of energy wherever compact and long-lived sources, not requiring maintenance, are needed. In the early 1970s, ^{238}Pu batteries were used as the power sources for cardiac pacemakers. Over 3,500 units were implanted and most remain functioning. Due to a lower cost and easier construction, lithium batteries have largely supplanted the plutonium.

Nuclear Weapons

Without a doubt, the development of nuclear weapons is one application of nuclear science that has had a significant global influence. Following the observation of fission products of uranium by Hahn and Strassmann in 1938, a uranium fission weapon became possible in the eyes of a number of nuclear scientists. It was Albert Einstein who signed a letter to Franklin Roosevelt, President of the United States, and alerted him to the potential development of a nuclear weapon. Thus began the Manhattan Project, resulting in production of the first nuclear weapons.

In 1945, a bomb using the fission of ^{235}U was dropped on Hiroshima, while a bomb using the fission of ^{239}Pu was dropped on Nagasaki. The awesome destruction that was produced by two nuclear devices changed the face of warfare forever. Not only did these two explosions end the most destructive war in history, but also the possessor of these weapons of mass destruction seemed invincible to any adversary.

The legacy of nuclear weapons remains in the soil around us, where we can still measure minute amounts of fallout from the atmospheric nuclear tests of the 1950s and 1960s. The weapons need constant maintenance because radiation damage affects the materials and triggering devices that must act together to make the weapon work. Furthermore, the isotope tritium, which is used in weapons, naturally decays. Storage and disposal of the weapons is technically difficult but probably a manageable problem. However, it is a daunting political and social problem. It is a challenge to maintain these weapons, to significantly reduce their numbers, to clean up the waste, and to insure that these weapons never will be used again.

Nuclear weapons are with us to this day and could be with us in the future. Even if all conflicts among nations end, some nuclear weapons might be retained. Earth is vulnerable to impacts from comets and asteroids. Some scientists have proposed that nuclear weapons could possibly be used to deflect them from hitting our planet.

Space Applications: Radiation-Induced Effects

Radiation-induced spacecraft anomalies have been known since the Explorer I launch on January 31, 1958, when a Geiger counter put aboard by J. A. Van Allen suddenly stopped counting. It turned out that the counter was in fact saturated by an extremely high-count rate. This led to the discovery of the Van Allen belts.

The inner belt, beginning at about 1,000 km above the surface of the Earth, contains primarily protons with energies between 10-100 MeV. The offset between Earth's geographical and magnetic axes causes an asymmetry in the radiation belt above the Atlantic Ocean off the Brazilian coast, allowing the inner belt to reach a minimum altitude of 250 km. This "South Atlantic Anomaly" is important because it occupies a region through which low-orbiting satellites spend as much as 30% of their time. During a solar flare, which can happen anytime, the number of protons suddenly increases by more than a million.

The first spacecraft loss due to total radiation dose effects occurred unexpectedly in 1962. A satellite, Telstar, was launched just one day after a high altitude nuclear weapons test. This weapons test produced a large number of beta particles, which caused a new and very intense radiation belt that lasted until the early 1970s. Telstar and six other satellites were lost within a seven-month period after this weapons test. Telstar was well studied and the loss was traced directly to breakdown of diodes in the command decoder due to the total radiation dose.

Radiation effects studies done at accelerators measure total-dose effects, displacement damage, or single event effects (SEE). A SEE occurs when one ion passing through a semiconductor causes enough damage to upset the circuit in some way. In 1978, the first SEEs were observed at ground level when Intel Corporation discovered that anomalous upsets occurring in dynamic random access computer memories were being caused by alpha particles emitted from trace amounts of thorium and uranium in the materials from which the device's packages were made. It was quickly found that massive ions, protons, and neutrons could all induce SEEs.

SEEs can result in the flip of a memory bit. This change can produce upsets with little other effect on the circuit. On the other hand, the effect can be more catastrophic causing and the chip could stop latchup and stop working. Sometimes powering down the chip will return it to life; for other times, it might burn out altogether or rupture a gate.

Biology Studies

Radiation biologists study the effect of radiation on living tissue. This field, that has direct analogies to the SEEs, examines the damage sustained by cells in the cosmic ray environment of space, a single event effect. These studies are necessary before we send astronauts to Mars.

Materials Studies

In 1959, it was discovered that mica that was exposed to fission fragments showed "nuclear tracks" when viewed under an ordinary microscope. This discovery led to a new class of nuclear physics detectors as well as a wide range of practical applications in earth science, oceanography, biology, medicine, archaeology, and space science.

By exposing thin sheets of plastic or other material to massive ions, tracks can be made through the material and then etched to make very fine "micropore" filters (30 nm to 8 μm hole size). These have been made at reactors since about 1970 and are used primarily in the biomedical field, with other applications in geophysics, meteorology, and brewing.

Another use for these sheets of plastic is to measure radon levels. By counting the number of ion tracks left in the plastic, one can measure the radon concentration.

Books and Articles:

P. Morrison and K. Tsipis, "New Hope in the Minefields," *Tech. Rev.*, **100** (7), 38 (1997).